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CONTROL OF MULTIPLE-UAVs: A WORKLOAD ANALYSIS

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Fifty-four licensed pilots carried out multiple surveillance missions on two high-fidelity simulations representing unmanned aerial vehicles (UAVs). In Experiment 1, pilots were required to operate a single UAV through three different mission conditions: a baseline condition, one that offloaded relevant information to the auditory channel, and one that provided automation of flight path control. In Experiment 2, pilots operated two UAVs simultaneously through the same three mission conditions. Pilots were responsible for the following tasks: a) mission completion, b) target search, and c) systems monitoring. Results of the experiment suggest that automation and auditory offloading can be beneficial to performance by reducing interference between tasks and thus alleviating overall workload.

1. INTRODUCTION

The Army has spent considerable time and energy developing UAVs, including the Hunter and Shadow, which have been used effectively in surveillance missions (Barnes, Ghiradelli, Stachowiak, Hill, & Dahn, 2002). However, the demands of piloting a UAV currently require that two operators fulfill the necessary mission requirements. An AVO (aviator operator) is responsible for aviating and navigating the UAV, while an MPO (mission payload operator) searches for targets and monitors system parameters. Since having two operators limits the number of UAVs available for combat, the Army would like to examine the feasibility of merging the responsibilities of the AVO and MPO into a single entity without triggering excessive workload demands on the operator. The purpose of the two experiments in the current research is to address these issues.

The term “workload” can be defined as the relationship between resource supply and task demand (Sarno & Wickens, 1995). If this supply of mental resources exceeds demand, performance should remain constant; however, when demand imposed by competing tasks exceeds the existing supply of resources, performance is expected to suffer. Furthermore, it is predicted that more resource demand results in more task interference, and thus further deficits in performance. Intuitively, the UAV challenge could require more resources than are readily available to the pilot, particularly when one operator is suddenly responsible for performing multiple tasks previously divided between two operators.

There are a variety of theoretical proposals that attempt to account for task interference; we present three of these theories and outline how their subsequent models predict performance. (1) Single Channel Theory developed from research suggesting that simultaneous processing of two concurrent tasks is virtually impossible and that the time required to fulfill multiple tasks is the sum of all tasks (Welford, 1967; Broadbent, 1958; Liao & Moray, 1993). Subsequently, any attempt to offload a task to a different modality (e.g., converting a visual display into an auditory presentation) will have no effect on performance unless task times are reduced. Introducing automation will only be effective if it totally replaces the human responsibilities of a task. (2) Single Resource Theory proponents argue that parallel processing is possible, and that task difficulty, not time, modulates task interference (Kahneman, 1973), with difficult tasks creating more interference than simple tasks, irrespective of the time it takes to accomplish the task. Multiple Resource Theory expands on this concept by suggesting that two tasks which use different resource structures, such as the auditory and visual systems, will facilitate better parallel processing than two tasks which use the same resource structures (Navon & Gopher, 1979; Wickens, 2002). These three theories spawn different workload models that make different predictions regarding the effectiveness of offload strategies presented in the current research.

In Experiment 1, we present pilots with three different mission conditions while flying a single UAV, in order to measure the effectiveness of offloading relevant information to the auditory channel and of providing automation aids to support flight path control. In Experiment 2, we extend this paradigm to a dual-UAV scenario in order to examine these same issues under multiple-workstation conditions. In both experiments, we examine the feasibility of the three different models to account for the workload (task interference) data.

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2. METHODS

The UAV simulation ran on an Evans and Sutherland SimFusion 4000q, with dual 1 Ghz PIII processors and an OPENsim Graphics card. The two interfaces, representing separate UAVs, were displayed on twin Hitachi CM721F 19-inch monitors (37-degrees visual angle), using 1280x1024 resolution. Figure 1 illustrates how the display for each work-station appeared.

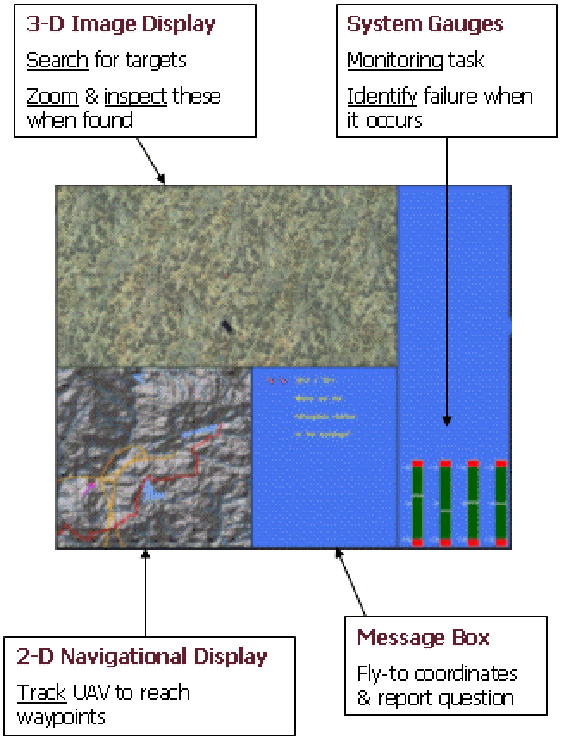

Figure 1. A sample UAV workstation with verbal explanations for different displays.

Each mission involved flying through a series of ten navigational legs and carrying out three major goal-oriented tasks: mission completion, target search, and system monitoring.

At the beginning of each leg, pilots were directed to read mission instructions displayed in the message box. This two-part message, which would remain visible for 15 seconds (presented once in the auditory condition), included fly-to coordinates, which the pilots would use to navigate to the next command target (CT), and a report question, which the pilots would respond to once they reached that target. If necessary, this message could be refreshed by pressing a repeat button. Upon arriving at the next CT, the pilots would enter an automated loiter pattern, zoom in with their camera to analyze the target, and report on what they found there. These reports required mental rotation (e.g., are there any weapons on the west and south sides of the building?), which is an extremely challenging task (Gugerty & Brooks, 2001).

Concurrently, pilots had to monitor the 3-D image display for possible targets of opportunity (TOO) which were located on a straight-line path between each CT. Upon detecting a TOO, the pilots were required to loiter, zoom, and analyze the TOO in much the same way as the CT.

Lastly, pilots were required to constantly monitor a system parameter display for possible failures (see Figure 1). The four system gauges would oscillate continuously, and infrequently go “out of bounds.” Pilots were required to detect these system failures (SF), report which SF had occurred, and enter ownship coordinates at the time of a failure. As shown in Figure 2, the SFs were designed to fail at certain strategic points along each mission leg: A) during initial orientation, B) during normal flight when no TOO was visible, C) 5 seconds after a TOO came into view, D) during a TOO inspection, and E) during a CT inspection.

The baseline condition was flown as above. The **auditory offload** condition was designed to relieve some of the heavy visual workload demands created by multiple displays. The system gauges were augmented by an auditory alarm when a SF occurred, and mission instructions were presented by synthesized voice. Multiple Resource Theory predicts that offloading this information to the auditory channel should facilitate better parallel processing. The other two theories make no such predictions.

The automation offload condition eliminated the task of manually flying the UAV. Instead, pilots needed only to enter coordinates on a keypad and then allow the autopilot to choose the correct straight-line path to the next CT. All three theories would predict that, by allowing reallocation of mental and physical resources to other tasks, performance in those concurrent tasks should improve.

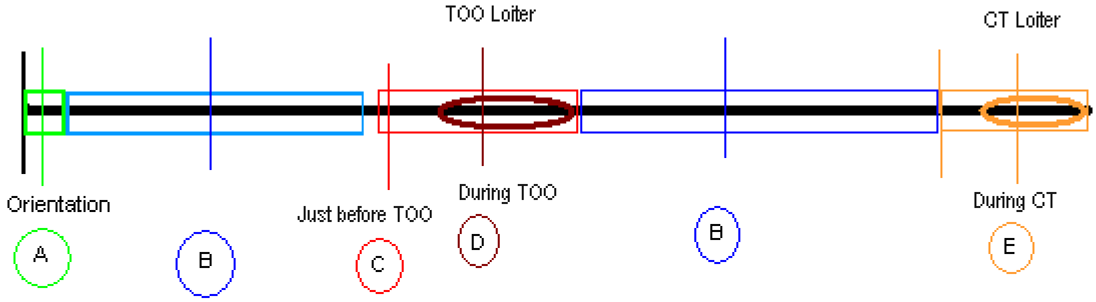

Figure 2. A timeline of SFs for a typical mission leg. Any leg would contain only one of the five different system false types.

3. EXPERIMENT 1

3.1 Experiment 1: Methods

Participants included 18 licensed pilots from the University of Illinois who were paid $8 per hour. Each pilot flew through three different 10-leg missions which lasted approximately 55-60 minutes: a) baseline condition with all manual control and visual displays, b) auditory offload, and c) automation offload. The missions and maps were counterbalanced across subjects.

3.2 Experiment 1: Results

The most salient aspects of Experiment 1 will be discussed here (see Wickens & Dixon, 2002, for a more detailed analysis). In general, these results seek to compare the differences between the baseline condition and the two offload conditions, rather than to make global comparisons between the three conditions.

3.2.1 *Results: Mission completion*. Tracking error was measured by RMS error off the straight-line path. By design, the automation condition provided perfect tracking; there was no difference between the baseline and auditory conditions. Neither response times nor accuracy to reporting command targets were affected by either offload. This suggests that pilots treated mission completion as the primary task and allocated full resources to this task even in the baseline condition.

As mentioned, pilots were able to refresh the flight instructions by pressing a repeat button. Both the auditory (13 times per mission on average) and automation (13 times) offloads enabled fewer repeats than the baseline condition (19 times), although for apparently different reasons. More detailed analysis of when repeats occurred during a typical mission leg show fewer auditory repeats throughout the entire mission leg, implying more effective parallel processing than in the baseline condition. In line with predictions made by multiple resource theory, this was probably due to the auditory presentation relieving critical visual resources. In the automation condition, there were only fewer repeats during the first 70-80% of the leg, suggesting that pilots refrained from refreshing fly-coordinates since they were confident in the auto-tracking aspects of the automation. Thus, the auditory offload allowed instructions to be better retained, whereas the automation offload mitigated the need to remember CT coordinates.

3.2.2 *Target (TOO) monitoring*. Manual tracking clearly had a detrimental effect on monitoring for TOOs when compared to the auditory condition [47% vs. 55%: $t(17) = 1.94$, $p < .05$] and to the automation condition [47% vs. 90%: $t(17) = 8.84$, $p < .0001$]. However, the small advantage the auditory condition held over the baseline condition only emerged when system failures (SF) occurred just prior to the TOO appearing in the 3-D display (see Figure 1). As shown below, pilots were able to detect and correct these types of SFs more quickly in the auditory condition, and thus were able to spend more time searching for TOOs.

In the automation condition, much of this improvement results from perfect tracking, which always carried the UAV directly over TOOs. However, even when pilots flew directly over the TOOs in the baseline condition, they still failed to detect substantially fewer TOOs than in the automation condition [66% vs. 90%: $t(17) = 3.57$, $p = .001$].

3.2.3 *System failure monitoring*. As seen in Figure 2, SFs occurred during five different points along a typical mission leg, each modulating the effects of the offloads differently. The auditory offload provided substantial benefits to both SF detection rates ($p < .05$) and response times ($p < .05$) for all SFs that occurred during routine flight orientation, tracking, and target search (i.e., SF_A, SF_B, and SF_C). However, when a SF occurred during target inspection (i.e., SF_D or SF_E), this auditory benefit was neutralized. The highly challenging task of analyzing a target apparently induced "cognitive tunneling" and the pilots were either unable to, or chose not to, respond to the auditory alerts.

The automation offload, on the other hand, only provided benefits to SF detection rates during the initial orientation and tracking periods of the mission leg (i.e., SF_A and SF_B), when the automation offload allowed reallocation of resources to other concurrent tasks. There was no benefit expected during periods of target inspection because all three conditions applied equally automated loiter patterns. No automation benefit was found, nor expected, for SF response times.

To summarize, both offloads either provided substantial benefits relative to baseline performance, or had neutral effects. Neither offload caused any performance decrements for any task. Benefits appeared to be observed most often in tasks that were affected by the offload (e.g., SF and instructions offered auditorially, automated tracking, etc.), although indirect benefits were seen in SF and TOO monitoring for automation offload, and TOO monitoring for auditory offload. Auditory benefits are explained by multiple resource theory, which predicts improved parallel processing when tasks are divided between different resource structures; while automation benefits, which free up time and mental resources, can be explained by all three theories.

4. EXPERIMENT 2

4.1 Experiment 2: Methods

Experiment 2 was identical to Experiment 1 with the following exceptions: a) 36 licensed pilots participated; b) in addition to the hourly rate of $8, bonuses of $10 and $5 were awarded to pilots who placed first or second, respectively, in their group of six, as a means of motivating pilots; c) each pilot completed both a counterbalanced single- and a dual-UAV scenario, but only under one of the three conditions. Pilots were instructed to place equal emphasis on all tasks, and in the case of dual-UAV flight, to place equal emphasis on both workstations. Events (e.g., TOOs, SFs, CT locations, etc.) placed within one workstation were independent of those placed in the other workstation.

4.2 Experiment 2: Results

4.2.1 *Mission completion*. Many of the results of Experiment 2 replicate findings in Experiment 1. For example, tracking error again benefited from automation, but not from auditory offload, either in the single-UAV or dual-UAV scenarios. Tracking did not suffer when adding a second UAV, either in the baseline or auditory conditions.

Command target response times and report accuracy were equivalent across all three conditions, in both the single and dual UAV scenarios. As mentioned, pilots were able to recall flight instructions by pressing a repeat key; use of the repeat key followed the same general trend found in Experiment 1, with fewer repeats in both the auditory ($p < .05$) and automation ($p < .01$) conditions when compared to baseline. Increased use of the repeat key was found during dual-UAV flight relative to single-UAV flight for all three conditions (BL: $p < .01$; AD: $p < .01$; AT: $p < .05$).

4.2.2 *TOO monitoring*. The automation condition facilitated consistently higher TOO detection rates than the other conditions [$F(2, 33) = 18.29$, $p < .001$], regardless of the number of UAVs, as seen in the absence of an interaction effect between condition and task load [$F(2, 33) < 1.0$]. When a SF_C occurred just prior to the appearance of a TOO, detection rates for TOOs dropped about 15% for all three conditions [$F(1, 127) = 4.40$, $p < .05$].

Response times to TOOs showed an automation-supported advantage of 5 seconds when compared to baseline performance, but only in the dual-UAV scenario [$t(21) = 1.86$, $p < .05$]. Apparently, automated tracking on one workstation allowed pilots to reallocate resources to the other workstation, resulting in more rapid target inspection. The auditory condition, however, showed no such benefits to TOO monitoring performance or response times, in either the single- or dual-UAV conditions.

4.2.3 *System failures*. As with Experiment 1, the auditory condition provided substantial benefits to SF detection rates [96% vs. 79%: $F(1, 206) = 19.16$, $p < .001$] and SF response times [3.59 sec vs. 8.77 sec: $F(1, 188) = 54.37$: $p < .001$]. Automation provided some benefit to detection rates [88% vs. 79%: $F(1, 214) = 5.15$, $p < .05$], but not to response times.

A dual-UAV decrement for detection rates was found only for the automation condition [$F(1, 110) = 6.94$, $p < .01$], while a dual-UAV decrement for response times was found for the baseline [$F(1, 89) = 4.05$, $p < .05$] and automation [$F(1, 106) = 5.42$, $p < .05$] conditions.

Figure 3 plots the SF response times as a combined function of when the SF occurred along each mission leg (i.e., SF Type), the number of UAVs (Single vs. Dual), and the interface condition (baseline, auditory, and automation). The graph reveals a main effect of SF type [$F(4, 294) = 9.31$, $p < .001$], reflecting faster SF response times during periods of pure monitoring (i.e., SF_B), and much slower response times during periods of highly challenging target inspection (i.e., SF_D and SF_E). However, the interaction effect, [$F(4, 188) = 2.65$, $p < .05$], shows a much greater penalty for the baseline and automation conditions than for the auditory condition, which suffers very little when coupled with a concurrent target inspection task or when control of a second UAV is imposed [$F(1, 99) = 1.66$, $p = .20$]. Auditory offloading appears to preserve performance in the SF task even when: a) the side task is extremely demanding of mental and physical resources, and b) the number of workstations is doubled.

To summarize, results from Experiment 2 generally replicate the benefits of auditory and automation offloading found in Experiment 1, with many of these benefits augmented by dual-UAV control relative to single-UAV control. However, additional benefits in the auditory condition are found during SF_D and SF_E, which occur during target inspection. These additional benefits provide more evidence of parallel processing due to demands made on different resource structures, and less evidence of "cognitive tunneling" found in Experiment 1.

5. GENERAL DISCUSSION

Overall results from both experiments show advantages for both auditory and automation offloads, albeit for different reasons.

Auditory benefits were almost always exclusive to those tasks which applied an auditory interface. Clearly, auditory alerts for SFs resulted in better detection performance and faster response times, while auditory presentation of flight instructions resulted in fewer repeats. As predicted by multiple resource theory, offloading to a separate modality relieves critical visual resources and facilitates more efficient parallel processing. The other two theories, SRT and SCT, make no such prediction. Results from Experiment 2 show greater benefits of auditory offloading than found in Experiment 1, specifically when SFs occur concurrently with target inspection (i.e., SF_D and SF_E), suggesting that the preliminary finding of "cognitive tunneling" in Experiment 1may have been mitigated by our attempts to increase pilot motivation in Experiment 2. By offering monetary rewards for exceptional performance, pilots may have abandoned "strategic" serial processing in favor of concurrent processing.

In contrast to the effects of auditory offload, automation benefits appeared not only in those tasks which were directly affected by automation (i.e., tracking), but also in concurrent monitoring tasks. Increased detection rates for SFs and TOOs reveal that automating the primary task of flight tracking and navigation allowed reallocation of visual, cognitive, and motor resources to these other tasks. These findings appear consistent with all three models of task interference; that is, removing a task in its entirety frees up time (single channel theory) and mental resources (single and multiple resource theory), which can be reapportioned to other tasks. Admittedly, the current study employs only perfect automation, and future investigations will consider the impact of introducing automation failures (Wickens & Xu, 2002).

Regarding the workload of dual UAV control, while not excessive, there were substantial costs to performance when adding a second UAV. These costs were seen in SF monitoring, TOO monitoring, and flight instruction recall, but not in tracking performance or in target report duration or accuracy. This finding suggests that pilots treated mission completion tasks as "primary" and allocated sufficient resources to those tasks, often to the detriment of other tasks. Decrements seen in the secondary tasks were clearly due to competition for time and mental resources. Pilots often were faced with two simultaneous attention tasks on separate workstations, both of which demanded foveal vision, forcing them to choose a more serial approach to processing.

In general, a greater loss in dual-UAV performance was found in TOO monitoring than in SF monitoring, suggesting two possible non-exclusive explanations. First, pilots may have placed less emphasis on TOO monitoring because they felt that mission completion depended more on maintaining normal system parameters. Second, because SFs were more salient than TOOs, they required less foveal attention and may have benefited more from peripheral visual attention. That is, SF monitoring was better supported by attentional resources.

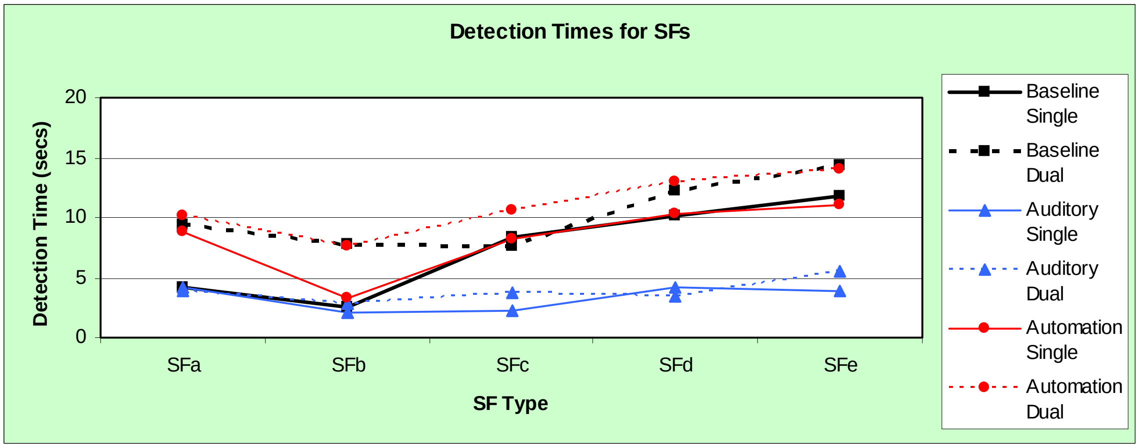

Figure 3. Response times for all types of SF.

Dual-UAV costs appeared to have been generally mitigated by the two offloading techniques, in patterns similar to those found in single-UAV control. For example, TOO detection performance benefited from automation in both the single- and dual-UAV conditions, while SF monitoring costs were eliminated entirely by auditory offloading in the dual-UAV condition. As with single-UAV results, all three task interference models provide reasonable explanations for benefits found in automation, while only multiple resource theory can explain the substantial benefits found in the auditory offload.

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